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MEMORANDUM FOR: D/DCI/NIPE

The attached monograph briefly describes some of the potential opportunities and problems for the Intelligence Community of the future.

/s/

25X1A

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GROUP 1
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A DESCRIPTION OF SOME OPPORTUNITIES AND PROBLEMS IN INTELLIGENCE

Opportunities

1. Exploratory research and development can now be profitably and effectively pursued toward the objective of establishing multi-sensor collection capabilities on a world-wide basis. Such a capability would allow most overt activities to be monitored to whatever degree may be desired. There is now significant activity in this direction, and it is clear that satellites and versions of the MOL, etc., could provide platforms to carry sensors or to communicate with sensors on or near earth. Activities which could readily be monitored include transportation movement, weather, various types of production, movements of groups or individuals, etc.

2. In addition to being able to collect and monitor, capabilities can be developed for the selection and assessment of data in near real time. The information explosion phenomena should properly be regarded as an opportunity since it permits selectivity of the data which will be considered, whereas in the past it often has been necessary to do a great deal of work with marginal information. Obviously, an exercise of judgment is required, and if this judgment is to be optimum appropriate tests for the importance of data must be devised.

3. Concurrent with the development of the appropriate sensor systems and their related communications and the development of criteria for the assessment and selection of data in real time, various economic models can be developed with which predictions of capabilities which will set feasible action limits can be developed. Such modeling can be extended into areas other than economic and, in fact, some criteria for such models based on observable actions and events are explicit in descriptions [redacted] of escalation and other national relationships. 25X1A

Problems

1. I feel the greatest obstacle to the exploitation of our opportunities is the attitude of people; inertia to change is real and cannot be overlooked. To some extent we have motor vehicle

capabilities, but require that the motor vehicle be drawn by horses, simply because we are used to thinking in terms of horses, and may also be organized along these lines. There are limits in our mobility both in developing concepts and in assessing those concepts in terms of their potential value. Perhaps the best and most effective method for changing our attitudes and perspectives is through the clear delineation of goals, and the resulting development of clear understanding among the important parties concerned.

2. In order to realize the opportunites increased lead time, particularly in the identification and selection of national goals, is required. Although the necessity for lead time in the engineering aspects of complex equipment is understood, there does not appear to be an equivalent appreciation of the necessity for systems studies and the development of logic as to how complex ensembles of equipment can be most effectively designed and used. It is important that this preliminary, vital, work be carried on continuously. Such studies will indicate needs for self-discipline in stating requirements and identify the requirements which are most significant. Because of the long lead time required, this work is often neglected, and sometimes, if it is started, the end goal is forgotten before the work is finished; the problem then includes continuity in the program.

3. The attached paper "The Automatic Control of Electric Power in the United States" identifies and exemplifies many of the opportunities and many of the problems which may be anticipated in the application of technology to the intelligence process. While the paper is of some interest because of the recent power failure in the Northeast, it provides an excellent illustration of technical capabilities for handling an extremely complex situation. Note in particular the necessity in controlling the generation of electric power for "feed forward". "Feed forward" is analogous to prediction in the intelligence process, and "feed back" also serves to modify the control process. Through a back and forth flow of these two processes an optimum control situation can be achieved. In the area of human factors and attitudes, it is interesting to note that operators still manually close some switches in the start up process. The control room console also shows a number of display devices by which the operator may monitor the operations. These displays and the analog processes described are, I believe, reflections of the reluctance of people to adopt techniques and equipment which is strange and foreign to their experience. There is a considerable spread in the degree of progress which has been

achieved in various power generating station equipment. This analogy probably fits the Intelligence Community also. Considered internationally, however, the disastrous consequences of being left technologically behind are apparent.

The automatic control of electric power in the United States

Automation of the electric power industry is well under way. Comprehensive coordinated control systems, derived from theory and practice, have been developed to solve complex multivariable control problems of the modern steam plant. Controls are primarily analog in nature but direct digital control is being investigated

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In reviewing the state of the automatic control art in a given field of application, it seems appropriate first to take note of progress in the field itself. Changes in process techniques or objectives define new requirements and opportunities for advances in control concepts and equipment. Accordingly, this survey article will endeavor to "close the gap" between theory and practice by doing three things: (1) review in brief the growth and progress of the power industry itself; (2) make some comments on recent significant trends and innovations in its processes insofar as they relate to major areas of automatic control application; (3) discuss the state of the art in these applications.

The electric power industry

A considerable portion of the economic growth and industrial strength in the United States relates to the growth of its electric power industry, which is by far the largest of the country's industries[1] (Fig. 1). In recent decades the electric power industry in the United States has been growing at a rate of about 7 percent per year, more than doubling its generating capability every ten years[2] (Fig. 2). At the beginning of last year, generating capacity totaled over 228 million kW.

Annual output of generating plants has been steadily growing over the years (Fig. 3), and is now of the order of 1000 billion kWh, or—using more modern terminology—1000 TWh (terawatthours). An interesting figure is that with only 6 percent of the world's population, the United States generates 37 percent of the world's power.

Power processes

Electric power processes are concerned with energy conversion and the delivery of energy to users in useful form, when and where and for as long as wanted, as economically and dependably as possible.

To help clarify these processes and their control problems, and to provide a basis for an orderly review of recent progress and present state of the control art in this field, two general areas in this review shall be considered, namely:

1. Energy conversion plants. The objective is to operate each plant at optimum efficiency at the power generation level assigned to it.
2. Interconnected networks of such plants. Here the objective is to assign and maintain plant generation levels and tie-line power flows that will yield optimum overall system economy consistent with continuity of system operation.

Generating plants

As can be noted from Fig. 3, over 81 percent of the present output of the industry is derived from fuel, and almost all of this is from fossil-fuel-burning steam-electric plants. In discussing progress in plant processes and automatic control applications within plants, this article will accordingly confine itself to such fuel-burning plants. That is not to say that other forms of energy conversion are not important, but time and space limitations will not permit their inclusion in this discussion beyond these brief comments:

Pumped storage. In a typical area, over a typical day, power demand will vary over a range of about two to one or more between the periods of highest and lowest demand. Power demand in the valley period is likely to be below the total capability of the most efficient available units, some of which would therefore have to be idle for parts of the day. There has been increasing interest in recent years in taking advantage of the variation in power demand by utilizing "pumped storage" for "peaking" purposes.[3]

Under some conditions it is advantageous, during off-peak hours, to use low-cost steam plant energy to

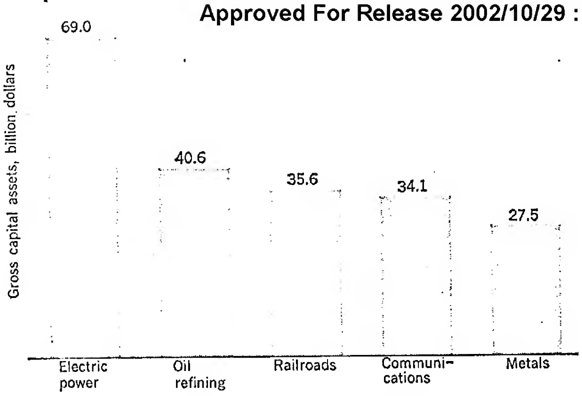


Fig. 1. Gross capital assets (in billions of dollars) of the largest United States industries in 1962.

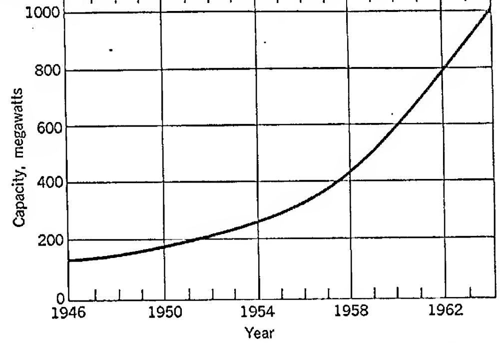


Fig. 4. Largest turbine–generator set, 1946–1964. Progressive growth in size of individual units.

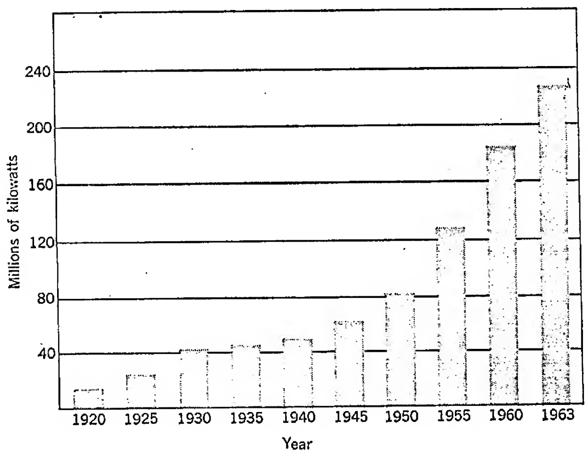
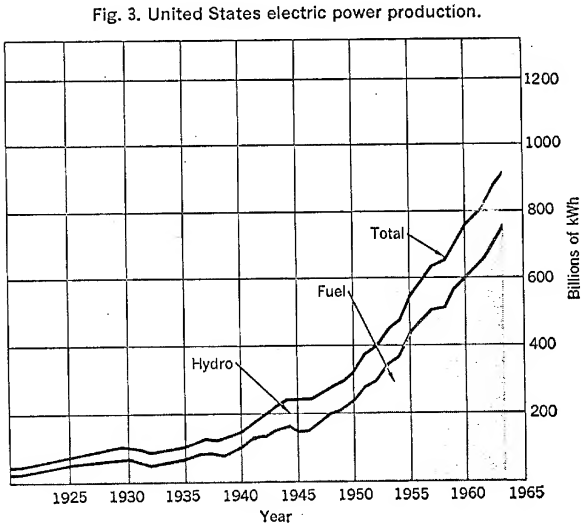


Fig. 2. United States generating capacity.

Fig. 3. United States electric power production.



pump water up to high-elevation reservoirs, and then run the pumps as generators during high-demand periods. About 2000 MW of pumped storage capacity is currently in operation or under construction. Several thousand megawatts of additional capacity are under consideration.

Control specialists will recognize that there are interesting optimizing challenges in the operation of such facilities.

Nuclear power. Nuclear plants at present account for only a small fraction of a percent of the nation's power capability. It has been estimated, however, that by 1980 nuclear power installations will aggregate about 70 000 MW, or about 13 percent of the total capability expected to exist at that time. Such plants will engender a particular awareness of economy and safety, and will provide many automatic control opportunities.

Fossil-fuel plants. Let us turn now to fossil-fuel-burning plants. Here a first major point of interest is the progressively increasing sizes of individual units.

The trend of increasing sizes is shown in Fig. 4. A typical size in 1950 was 175 MW (compared with 100 MW in 1940). A number of units in the 500–700-MW range are now in operation or under construction. Units of 900 and 1000 MW will start commercial operation within the next two years. A 1200-MW unit is already under contract.

Increased size has generally meant increased complication, with greater demands from, and greater dependence on, automatic control.

Paralleling the increased sizes, and reflecting continuing progress and improvements in the energy conversion process, has been improved efficiency. This is illustrated for the years 1930–62 in Fig. 5.

Best plant heat rate, which was 15 000 Btu per kilowatthour back in 1925 (not shown in Fig. 5), had improved to approximately 8600 Btu per kilowatthour by 1962. For *all* plants in operation the drop has been from 25 000 Btu per kilowatthour in 1925 to approximately 10 500 Btu per kilowatthour in 1962.

Such steady and significant improvements in plant efficiency have counterbalanced the continuing increases in the price of fuel over the years, permitting a fairly constant cost of fuel per kilowatthour despite the fuel price increases. These factors are illustrated in Fig. 6. Auto-

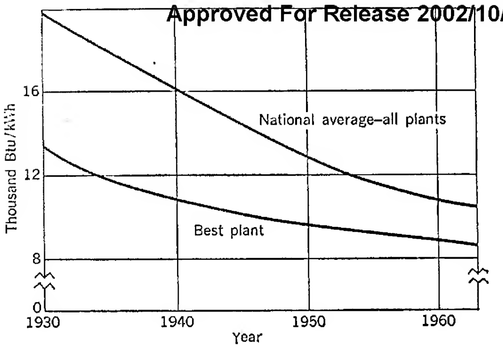


Fig. 5. Improvement in plant heat rates.

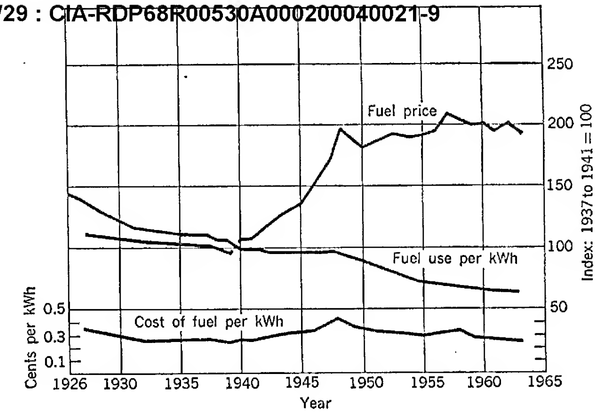


Fig. 6. Fuel prices and efficiencies, 1926–1963. Improved efficiencies counterbalance increased fuel prices.

matic control has played an important role in the achievement of these improved efficiencies.

The supercritical pressure unit. As part of the continuous search for improved operating efficiencies, design pressures and temperatures of steam-generating units have been steadily increased over the years. As a most noteworthy advance in this field, several units have been built and placed into operation within the past five years which operate in the supercritical range. Most units in the 500-MW and above size are or will be in this category.

When operating above critical pressure—3206 psi—steam and water do not exist as a mixture. A steam generator of this type is therefore of the "once-through" design. It has no steam drum with its storage effects, and drum level is therefore not available as a control reference as in conventional boilers. Its response characteristics and degree of self-regulation differ markedly from conventional units. It includes a very large number of manipulated variables, many of which have major interacting effects on output parameters. Its operating complexities are manifold. It has created the need for markedly new concepts and executions in an automatic control system that will provide stable coordinated regulation over the full range of "light-off" to rated load, under both steady-state and varying load conditions.

The solutions developed for such boilers are representative of the most advanced state of the art in this facet of power plant control.

In turning to more detailed comments on in-plant controls, I think it will be helpful to consider two aspects of such applications separately, even though they are to some degree interrelated, namely: (1) continuous operating functions, including on-line automatic control, performance computation, and safety monitoring; and (2) automatic start-up and shutdown functions.

Continuous plant controls

Use of control theory. In the development of present-day control systems, such as those now applied to once-through boilers, modern control theory and simulation techniques have been used, to a degree, to replace or supplement the essentially empirical approaches of earlier years. Simulation in particular, using both analog and digital computers, has been helpful in dynamic modeling,

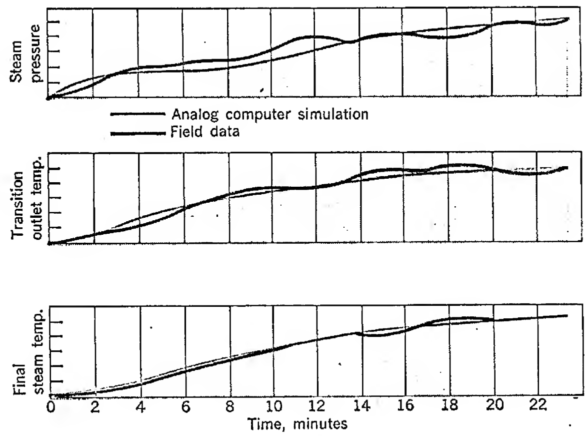
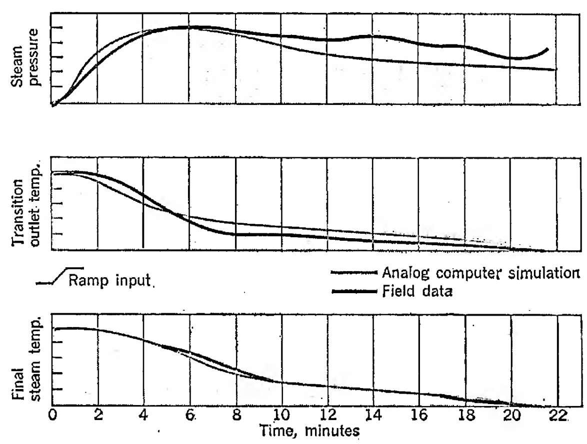


Fig. 7. Responses to step change in fuel and air at full load. Comparison of L&N simulation with field data.

Fig. 8. Responses to ramp change in feedwater. Comparison of L&N simulation with field data.



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in the development of advanced control concepts, and in the synthesis of multivariable control systems.[4-7]

Several companies feel that here, at least, a gap has been effectively bridged and that there have been productive exchanges between engineers with long-time practical power plant field experience and scientists in computer laboratories.

Simulations from theoretical design data of complex once-through units have proved to be reasonable when checked against subsequently available field data. Typical comparisons of predicted variations in output parameters for step function changes in input variables, based on a theoretical simulation of a supercritical once-through boiler from its design data, with subsequently available field data are shown in Figs. 7 and 8.

These simulations were conducted on an analog computer having 170 operational amplifiers, and, together with similar simulations, were helpful in carrying out significant studies and in reaching decisions on the relative merits of proposed alternative control arrangements. This manufacturer is studying supercritical unit responses more extensively on a large digital computer, and subsequently performing the control studies on an analog computer. With this approach, it has been possible to study all of the significant process inputs and outputs to represent all of the major control loops.

In addition to simulation, use is being made in modern control systems of noninteracting concepts, of feedforward techniques, and of adaptive arrangements to adjust controller settings for nonlinear control responses at varying loads and with different operating combinations.

Where direct digital control techniques have been undertaken, available knowledge of sampled data theory has been used to establish sampling rates properly related to input noise conditions and to process control dynamics.[8]

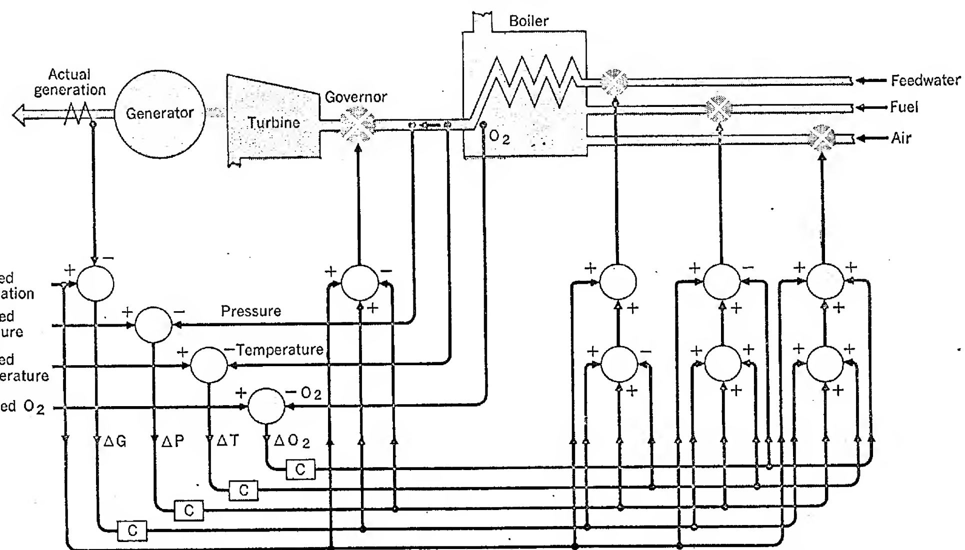
In general, manufacturers feel they are making commendable progress in the development of control concepts as coordinated noninteracting control systems to meet the exacting requirements of complex present-day plants. They might well be the first to grant, however, that not too much of the extensive control theories being developed, particularly in academic circles, finds use in present-day installations. Much that is done remains empirical or experimental.

Empiricism and experimentation. In the context of comparisons between theory and practice, it seems appropriate at this point to say a few words about empiricism, its practitioners, and its relation to control applications.

Empiricism should not necessarily be downgraded. Indeed, when it takes place in the most advanced of experimental laboratories it is usually called "science." In the development and application of control systems, empiricism is unscientific only when the attitude is obtuse and narrow, and when available applicable contemporary knowledge is not fully used.

Theorists should recognize that it is the empiricist, the "practical" engineer, who is largely responsible for the control systems that are installed and operating so well in complex generating plants and on widespread interconnected systems today. Typically, he has gathered much of his information and understanding from field observations and experiences, from adjustment of control systems in customer plants, and from cut-and-try techniques for improving their performance. He has sought to absorb and utilize all the applicable theory he can understand. In addition, the most effective empiricists have listened with respect to the more theoretically minded individuals at their plant headquarters who

Fig. 9. Simplified schematic of a coordinated control system for once-through boilers. Major coordinating controllers are marked "C."



have been able to demonstrate better ways of anticipating and solving field problems and better ways of executing recognized control principles.

But there is one view from which the practical engineer cannot depart. Today's control problems need solutions today. Customer commitments must be satisfactorily resolved with contemporarily available tools. Tomorrow's knowledge will not be today's until tomorrow, and will not become fully useful until then.

The practical engineer recognizes, however, the importance of innovation, and he encourages all activity that will improve the state of the art. But he also recognizes that newness does not necessarily equate with progress. He welcomes innovation, but requires that what is new be proved, in actual operation, to have appropriate qualities of reliability and improved performance before it qualifies for general acceptance as a contribution to the art.

I am certain that all manufacturers are on the alert for, and ready to welcome, all theoretical contributions, from within and outside their organizations, that will help them do a better practical applications job.

A coordinated control concept. Let us turn to the synthesis of a coordinated control system for a complex multivariable application. One control now in use and being supplied for new projects, derived from both theoretical considerations and field experimentation,[4] is shown in highly simplified form in Fig. 9.

The large-sized once-through units to which this system is currently being applied have as many as 90 or more manipulated variables to be placed under coordinated automatic control. The diagram of Fig. 9 does not by any means begin to show the extent of the control problem, with its multiple fuel, air, and feedwater inputs, its reheat steam cycle, and its complicated, almost endless details. The diagram is intended only to show how the major input variables are acted on in coordinated fashion by pertinent measured, set, and computed parameters, in some cases in the same sense, in others in the opposite sense.

Feedforward from desired output, itself manually set at the station or automatically set by a remote dispatching computer, is utilized. Appropriate limits for ranges and rates of response are provided, as are automatic runbacks on loss of major auxiliaries. Each individual control action is conditioned to give weight to its influence on process output parameters, to varying response characteristics, and to varying time lags. These sophistications, essential to coordinated nonhunting and safe regulation, are not shown, but perhaps this brief reference to them will help to establish the dimensions of the control problem.

Analog executions. Virtually all major plant control systems currently in operation or in the process of installation are analog in nature. A recent trend has been to all-electric and electronic executions, though a number of the new large plants still favor pneumatic or electronic–pneumatic assemblies. Electric–electronic systems are felt by many to have the advantages of speed and flexibility, and they coordinate well with digital data and computing systems.

The newest analog systems make extensive use of solid-state technology. Increasingly, SCR power switches are replacing electromechanical contactors for operation of large electric actuators. Characterizable contact-free transmitters are replacing potentiometers for generating actuator feedback signals.

There have been important improvements in the accuracy and reliability of flow and pressure transmitters, but even greater performance capabilities are being requested by users.

Digital techniques. Power companies have been traditionally alert to the need for collecting data for operator guidance and for evaluation and improvement of plant performance. Where a company's fuel bill runs into many millions of dollars per year, big savings can be achieved by even modest improvements in plant efficiency.

Several years ago, conventional measuring and recording instruments began to be supplemented, and in some instances replaced, by digital data gathering assemblies. Some of the systems included modest computing capability. Pertinent information was in this way presented to operators in a more centralized and coordinated fashion, hopefully resulting in more rapid corrective steps when such were required.

With the advent of the digital computer, centralized data gathering systems were expanded to include additional functions.[9]

One objective was to provide the operator with concurrent computations of cycle and plant efficiencies instead of the previously available historical analysis. Another was to provide more extensive monitoring and alarm functions, which would aid in preventing both minor and major shutdowns. Efforts to extend the computer to plant control functions soon followed.

In addition to these essentially continuous plant functions, computers were also installed to fully automate plant start-up and shutdown without human intervention, as will be additionally referred to in a section that follows.

The pioneer on-line solid-state digital computer installation was made in 1958. Its functions were logging of approximately 100 key variables, alarm scanning, performance calculations, and closed-loop direct digital control of two auxiliary temperatures.

Since then, it is estimated that about 65 or 70 computers have been installed in steam plants throughout the country and additional ones are in the process of installation.

As experience has been gained, and new generations of computers have become available, functions have been extended to larger numbers of points scanned, alarmed, and logged, to more meaningful and useful performance computations, to logical sequence control functions and—in a few cases—to more extensive direct digital control.

There is by no means agreement in the industry at this point, however, on the functions that can and should be assigned to a plant computer.

One example of current practice is shown in Fig. 10. This is an artist's sketch of the control room for a large plant now under construction. For each of two 900-MW units, control will be of the analog electric–electronic type, and a digital computer will perform monitoring, performance computation, alarm, and logging functions. Start-up and shutdown switching functions will be manually executed, but the computer will provide sequence and safety monitoring instructions and checkback for operator guidance. The screen for projecting monitoring messages to the operator can be seen in the center of the figure.

Another comprehensive installation, scheduled for operation this year, and exemplary of the present state of the applications art for steam-plant computers, will include the following functions: off-normal alarming, performance computation, logging, trend recording, on-demand display of stored history of plant variables, trip sequence monitoring, some start–stop functions, digital data control for several temperature and level loops that completely replace analog loops for these functions, and digital override of major analog loops for control of feedwater, combustion, and steam temperature.

Design, installation, and operating experiences with computer installations have been well documented.[10-14] (References 10 and 14 are particularly helpful in portraying the present state of this art.)

In general, I think it is clear from available documentation that there has been much to learn in applying on-line computers to power plants. In many cases, the experience has been time consuming and expensive, for manufacturer and user alike.

One manufacturer, in providing information for this survey, has cited a number of typical problem areas encountered with field installations. For most problems, he points out, solutions have been provided. For others, he notes, solutions still require verification.

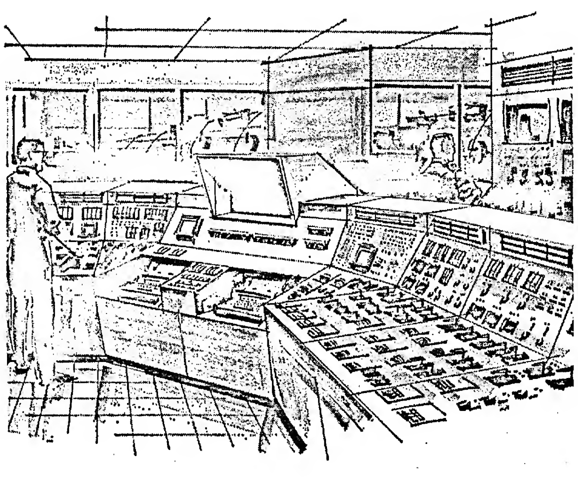
The problem areas cited are: input signal noise, system reliability (now felt to be of a high order), expansion capabilities, computer speed (solved with presently available units), transducer failures and errors, high cost and excessive time required to define, code, and check out programs (emphasized as a continuing real and major problem), and poor operator/computer communication.

Start-up and shutdown functions. An understandable objective in the operation of steam plants has been to extend the use of the digital computer beyond continuous monitoring, computation, and control functions to extensive start–stop functions, thereby achieving full plant automation.

One of the pioneering utilities in this aspect of computer application has stated in the following way the full degree of automation that it hoped to achieve: "The boiler and turbine–generator should be capable of being safely and reliably started, operated automatically at optimum efficiency, and automatically shut down without benefit of manual operator assistance."

References 11 and 13 document this company's and its consultant's experiences, and detail the extensive complications and problems encountered in undertaking so comprehensive an objective. While indicating that concrete evidence had not yet been developed that a digital computer system is the most economical method of automating a steam plant, they do call attention to benefits gained from experiences with efforts to achieve such full plant automation.

Fig. 10. Centralized control and monitoring, large supercritical unit.



Prevailing views

There is not, at this point, a unanimity of views among users and their consultants concerning the place of digital computers in steam plants. Performance of present installations is being appraised. Technical and economic considerations with respect to future plants are being evaluated. Here are excerpts from comments obtained from major consultants and operating companies for this survey article.

Consulting engineers. One consultant says: "Analog systems will continue to be used for automatic boiler control. There does not appear to be justification from the standpoint of initial cost or improved efficiency to encourage development of digital techniques in this area.

"It is for on-line up-to-date performance computation and safety monitoring that the computer initially derives its justification. Eventually, performance calculations will be standardized on a national basis, after which it is expected that such computers will be considered standard equipment for new projects.

"Due to the high equipment cost and complexity of programming for intermittent start-up and shutdown functions, and based upon reports of operating experience in this area, we cannot find justification for providing computer equipment for this purpose on an overall unit basis. We do recommend that consideration be given to computer start-up and shutdown in some areas, such as the turbine–generator combination, where programs have been successfully applied.

"Solid-state logic circuitry lends itself to start-up–shutdown functions as exemplified by progress in the burner light-off area.

"Overall start-up and shutdown appear to be a job for solid-state switching circuitry working in parallel with a computer."

Another consultant writes: "A direct economic justification by savings in efficiency and safety is almost impossible to prove. Another approach is that of demonstrating how small an increment of efficiency is sufficient to cover the cost of a computer installation, and assuming that the potential for such savings is inherent in a modern on-line installation.

"Once this concession is made, it would appear reasonable to justify an on-line computer for a large station by the many protective possibilities it presents in addition to performance calculation.

"While computer automated stations have yet to prove their worth, there is little doubt that this is the way the wind blows. A great deal of work remains to make

sensors more reliable, and to develop systematic methods for flow charting operations."

Still another consultant writes: "Any increase in the extent of automation must contribute to greater safety to both personnel and equipment, improvement of operating and operator efficiency, increase in station availability, and reduction of maintenance.

"All of the automation equipment must be justified by such criteria. When we consider highly sophisticated digital computing systems, justification tends to be based on more of the intangible advantages. It is extremely difficult to assign tangible values to such things as preventing catastrophic failures.

"Complete automation will be an integrated overall approach where some systems are independent and others are supervised by a stored program computer.

"Wide acceptance of advanced automation must develop slowly, and must be based on sound economic justification."

One consultant sees real potential worth of expected benefits from full automation, on a basis of fuel economy, minimization of manpower needs, reduction in maintenance, and reduction in both major and minor mishaps. "Expected savings," he points out, "can vary considerably with staffing practices, unit characteristics, and care in operation. For the same size units savings may vary by a factor of 3. Individual study is therefore essential."

He feels that direct digital control has promise, and cites the possibility of digital programs being used protectively to catch analog control failures before great upsets occur.

"Efforts to compute efficiency and heat rate are restricted by lack of solid understanding of heat storage dynamics. We need a full range nonlinear simulation. We live with imperfect sensors and position switches. A major problem is getting people with the right temperament, knowledge, and interest to work at bridging the gaps. We're still in R&D for the next couple of jobs."

Users. One of the users writes: "There are three drawbacks to computer control at present. They are the high cost of equipment, the high cost and effort required for programming, and lack of reliable sensing devices for many applications.

"We have not seriously considered digital computers for continuous control functions. We have felt that the most promising application is the continued use of analog loops with the digital computer used to control the time sequence of major operating steps and to make certain logical decisions."

Another user furnished a copy of reference 14, in which he comments about the future this way: "It is hoped that the two-year slippage of computer-controlled start-up at [Plant P] will be over in mid-1965. It is also hoped that experience will be achieved earlier at [Plant B]; however, the general inability of boiler, turbogenerator, and other contractors to produce on time the necessary information for analysis and flow-charting has already delayed completion of logic diagrams by 17 months. Programming for control has not yet begun [February 1, 1965], and the 12 to 13 months estimated for this work cannot now be completed by the commercial operation date. These comments are an acknowledgment of underestimating the job and overestimating ability in varying degrees by all participants. The worst effect is not getting any practical operating experience in computer control before having to proceed with another unit installation. In short, we have so far been unable to prove monetary savings equal to or exceeding cost of the systems. Information on costs however seems to accumulate steadily. Automation in various forms and degrees will continue to be applied until further experience and operating data dictate the requirements in a more adequate manner."

Another user, who has pioneered in plant automation, writes: "With regard to our present policy concerning automation, we are only making provisions for the future addition of computers. Conventional control systems are used. Automation features are included, but as wired logic subloops.

"We have retrogressed somewhat from our initial automation philosophy which was fully automatic start-up and shutdown programs with absolutely no manual interventions, to a more comfortable position which allows operators to perform most of the on–off type functions.

"It is true our new unit design lacks the degree of checks and balances afforded by complex computer programming, but with the automation we are providing in new units, the operator has at his disposal more control apparatus with which to circumvent plant hardware or control equipment troubles. Where set computer control programs provide a start-up procedure, increased remote manual control provides a start-up flexibility that has been lacking in all computer control programs to date."

Finally, still another user has this view: "More reliable primary sensors are needed to eliminate paralleling for redundancy.

"A great deal of effort should be expended toward application of digital techniques to present analog control functions. Other power plant processes which are at present inadequately sensed and controlled should be studied for digital control application."

It is clear from the foregoing summary of viewpoints that widespread differences of opinion currently prevail as to the degree of steam plant automation that is justifiable or desirable, and the extent to which it should be analog or digital or both.

Probably the best way to appraise the state of this facet of the art is simply to say that it is in a state of flux.

Views have certainly not yet hardened. Utilities and their consultants, to their credit, have encouraged experimentation. Not all the approaches or innovations have been the same, and not all the results have been satisfactory. Such uncertainty and differences of view are as good an indication as any that progress is being made. Work, in many plants, involving many manufacturers and consultants, continues. Inevitably, better clarity will emerge in the years ahead, and more universally shared views will doubtless develop.

Interconnected systems

Increasingly, over the past four decades, adjacent power companies have interconnected with one another for parallel operation. By this means, generation and reserves can be shared. Advantage is taken of load diversity and of time-zone differences to transfer generation over interconnecting tie lines from an area of low demand to one of high demand. Larger, more efficient units can be purchased and their outputs shared, and rotating reserves in a given area reduced. Overall operating economies are correspondingly achieved.

In earlier years, interconnections extended over relatively limited areas. As operating problems were analyzed and resolved, and parallel operation technologies were developed, interconnections have been steadily expanded. Today, five operating interconnections account for the entire country. The largest interconnection extends to the east from the Rocky Mountains, and includes the Midwest, the Gulf Coast, the Eastern Seaboard, and eastern Canada. Constituent groups within this single interconnection are the Interconnected Systems Group (ISG) of 115 operating utilities, private and public, the Pennsylvania–New Jersey–Maryland pool (PJM) of 12 operating companies, and the Canadian–Eastern United States group (CANUSE), which has 31 operating utilities.

The more than 150 utilities of this interconnection, having a total peak load greater than 130 million kW, operate continuously in parallel, smoothly and cooperatively. Automatic control makes that possible.

Similar parallel operation is achieved and automatic control is similarly utilized in the four other interconnections.

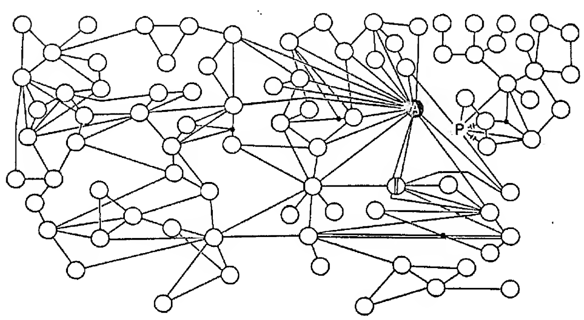
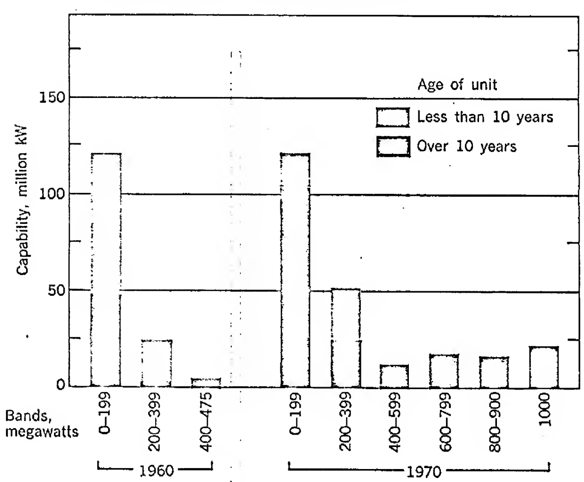


Fig. 11. Control areas of the country's largest interconnection (ISG, PJM, and CANUSE).

Fig. 12. Varying sizes and ages of available generators. Distributing of thermal generating units.



Some of the five interconnections have undertaken short-term test periods of parallel operation with each other. It is generally anticipated that by about the end of this decade requisite new tie lines will have been built and closed, permitting all five interconnections to operate as a single interconnection covering the entire United States and portions of neighboring nations.

The control problem

Coordinated control is essential to successful parallel operation. Concepts for system regulation and optimization have been well developed over the years, and are in widespread use within the limits of present-day equipment and technologies.[15]

Control requirements are twofold:

Area regulation. Total generation within an operating area must be adjusted to follow the moment-to-moment load changes within that area, in suitable coordination with generation and load changes in all other operating areas, so that scheduled tie-line interchanges with adjacent areas, system frequency, and system synchronous time are all properly maintained. This function is referred to as "area regulation."

Economic dispatch. Optimal assignment of the total generation required at any moment from an area should be made among the many plants and units within that area to achieve optimum economy consistent with safe operation. This objective is identified as "economic dispatch."

Let us explore briefly the nature of these two functions, and the present state of the art in achieving them.

Area regulation

The word "area" probably needs to be explained. An "area" can be a part of a company, a whole company, or a group of adjacent companies, which operate, from the viewpoint of interconnection, as a single entity. It schedules and maintains levels of tie-line interchange with its neighbors, but permits tie lines *within* the area to be free flowing; i.e., no effort is made to maintain them at any scheduled levels. All load changes within the area, regardless of where they occur, are treated alike insofar as automatic control is concerned.

A first objective of area regulation is to automatically adjust total generation to match total load changes within the area. A second objective is to adjust area generation when required to assist on a preprogrammed basis any other area of the interconnection that may be in trouble, and which cannot at the moment fulfill its own area regulation obligations.

The universally accepted technique by which coordinated neighborly area regulation fulfilling both of these objectives is achieved is known as "net interchange tie-line bias control."

The country's largest interconnection (ISG, PJM, and CANUSE) has some 88 control areas for its 115 operating utilities. These areas, with their major tie-line interconnections, are shown in Fig. 11. It will be understood that each circle is a control area, and may include, as several of them do, a number of companies "pooled" together to operate as a single entity from the viewpoint of area regulation and economic dispatch. Also, each line between two areas may represent many tie lines, and not just a single tie.

This interconnection extends into Quebec in the North-

east, Florida in the Southeast, a portion of Texas in the Southwest, and Montana and the Dakotas in the Northwest.

All 88 of the operating areas shown in Fig. 11 are equipped for net interchange tie-line bias control.

The tie-line telemetering required for the automatic computation of an area's net interchange with the interconnected system is largely analog, although in recent times digital techniques have also been used. Telemetering transmission has increasingly been by microwave.

Almost all of the area controllers, including most of those that have been recently installed, are of the analog type, the newest using solid-state components. One or two on this interconnection, and a similar number on the Pacific Southwest–New Mexico interconnection, use digital control techniques for area control function; these will be referred to further in discussing the use of digital computers for the economic dispatch function.

Area regulation performance. Area regulation performance on the interconnection of Fig. 11, though by no means perfect, has been very good. A commendable job is being done, permitting the areas of this widespread network to achieve the benefits of parallel operation and to stay together in operating synchronism, even during periods of large system disturbances.

It is no mean task to assure that 88 controllers, spread out over thousands of square miles of area—each in an independent privately or publicly owned utility, each depending on widespread telemetering networks, each requiring frequency and tie-line schedule settings coordinated on a system-wide basis, each requiring appropriate "bias" settings, each to be backed up by adequate and responsive generating capacity, each to be adjusted so that it corrects errors and does not create them, and all operating simultaneously on a single integrated network—will effectively fulfill their individual objectives and obligations and at the same time contribute to the common overall network objective of sustained, stable parallel operation.

That these complex control objectives are achieved as well as they are is a credit not only to the state of the applicable control art, but also to the operating people around the interconnection who are charged with making the system and its equipment work.

For many years there have been informal, voluntary operating and test committees on the various pools and interconnections who have appraised performance, analyzed problems, and established operating guides, thereby contributing immeasurably to the results currently being achieved. More recently, an informal, voluntary nationwide group, the North American Power Systems Interconnection Committee (NAPSIC) has been formed, with representation from all operating regions of the country, to deal on a national basis with the coordination problems of massive networks. This committee will make important contributions to improved system operations.

With regard to area regulation control performance, the refinements still to be achieved are: better and more rapid responses in some areas to changes in demand within the area; minimizing the regulating assistance required from other areas; fuller coordination of tie-line schedules; better telemetering channels for more sustained communications between tie lines and control, and between control and regulated generators; better coordination of frequency settings for time-error correction.

Improvement in all of these factors will decrease present levels of "inadvertent" interchange—i.e., deviations from scheduled interchanges between areas—and will assure equitable distribution of system regulating burdens.

Economic dispatch

In the execution of area regulation, generation is automatically adjusted within the area to match area load changes. Clearly, it would be advantageous to assign each required generation change to sources within the area that can most economically absorb it. If we take into consideration the different ages and sizes of units (Fig. 12), the resultant differences in their efficiencies, and their different locations and consequent differences in transmission loss factors to load centers, there is opportunity for substantial economies by loading them optimally with respect to one another. This is economic dispatch. It is achieved when generating sources within the area are loaded to equal incremental costs of delivered power. For fuel-burning plants the well-known coordination equation for such optimization is

$$\lambda = \frac{\dfrac{dH_n f_n}{dP_n}}{1 - \dfrac{\partial P_L}{\partial P_n}} \qquad (1)$$

where

λ is the incremental cost of power delivered for the area

$\dfrac{dF_n}{dP_n}$ is the incremental cost of power generated at source n

$\dfrac{\partial P_L}{\partial P_n}$ is the incremental transmission loss for source n

$\dfrac{dH_n}{dP_n}$ is the incremental heat rate for source n

f_n is the cost of incremental fuel for source n, adjusted to include other varying costs at source n

There has been an interesting evolution in the automatic control equipment used to achieve economic dispatch. A brief summary of some of its highlights and comments on the present state of the art follows. Those interested in fuller details of early steps in this evolution and in information concerning the derivation and applications background of Eq. (1) are referred to papers listed in the bibliography of Ref. 15.

Flexible loading consoles. The first areawide automatic economic dispatch systems date back to the early 1950s. Kilowatt loading schedules for each controlled source of the area as a function of total area generation were computed in advance, and were manually programmed into a centralized computer-control console. As area demand varied, the centralized console and its auxiliary equipment would compute and maintain the proper loading level for each generator of the area, and in the process would fulfill the area regulating requirements.

A unique and important feature of these control assemblies was the use of a feedforward signal from area control error, which, when combined with feedback from prevailing area generation, provided a reference for pre-

dictively computing the loading assignment for each source. This assignment was then independent of the rate at which other participating sources responded to their control assignments.

Another important feature involved arrangements for overriding economic dispatch when the area regulating requirement would not be fulfilled rapidly enough by the sources responding to economic dispatch.

A large number of these early consoles are still in use, and a number of new ones have been installed in quite recent times, some for predominately hydro areas[16] where the flexibility of wide-range schedule setters is very useful, and others for coordinated use with digital computers, as will be noted later. The newer assemblies utilize solid-state circuitry in place of the electromechanical elements of earlier units.

Analog desired-generation computers. An advance from the flexible loading consoles occurred in the late 1950s with the introduction of analog-computer-control assemblies based on the coordination relationships of Eq. (1). Here desired generation for each available source was computed on a continuous basis from the following:

1. Stored information of its incremental heat rate vs. output relationship.
2. Incremental transmission losses for its station, computed dynamically from continuous measurement of prevailing area generations and power flows and from stored constants related to the area configuration.
3. A continuously computed lambda value that would yield an economic dispatch whose total generation would satisfy the prevailing area needs.

Some two dozen or so large centralized analog computer controls of this general type are currently in operation, or in the process of installation. A combination of feedforward and feedback, as with the flexible loading consoles, provides a predictive lambda computation and contributes to nonhunting simultaneous control of area sources.

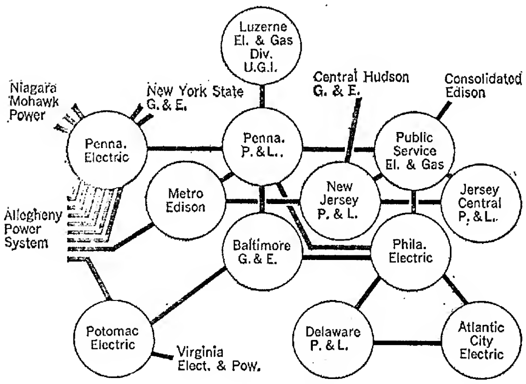
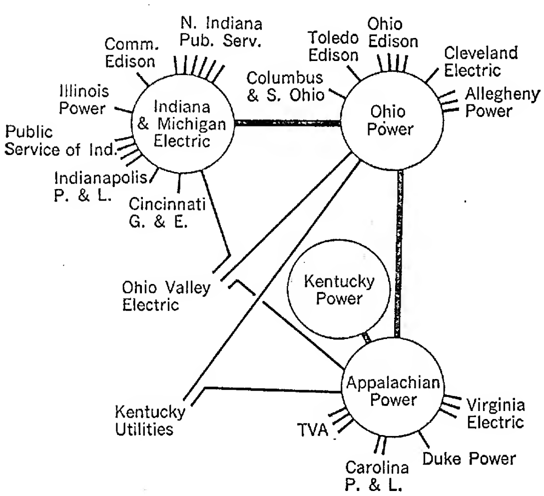


Fig. 13. Operating companies and ties of the circle marked "P" in Fig. 11. Pennsylvania–New Jersey–Maryland pool.

Fig. 14. Major operating companies and ties of the circle marked "A" in Fig. 11. American Electric Power System.



Digitally directed analog control. A relatively recent development has been the inclusion of digital computers in centralized economic-dispatch control systems. One technique is to link the digital computer to an analog console of the general type discussed earlier.[17-19] With this arrangement, the digital computer at appropriate intervals executes the economy dispatch computations, and transmits the resultant desired generation levels for the controlled sources to setting devices in the analog console. The latter executes the control assignment, achieving the economic dispatch while simultaneously fulfilling the area regulation obligation.

The digital computer can advantageously be programmed for other on-line functions, such as determining the appropriate time to bring generators on the line or take time off as peak load goes through its daily peak and valley cycles, checking reserves and imposing security restraints for various parts of the area, evaluating possible advantageous interchanges for neighboring areas, optimizing pumped hydro operation, checking area voltages, and logging pertinent operations and measurements data.

When the digital computer is not available for economic dispatch because of off-line use, or because of maintenance or malfunctioning, the analog console provides continuity of multiple-unit area regulation while executing manually programmed economic dispatch.

Several digitally directed analog systems have recently been placed in operation or are presently being installed.

Direct digital control. An alternative technique when utilizing a digital computer is to apply it directly for area regulation and economic dispatch, without the use of an intermediate analog control console. At the present state of the art, a suitable stand-by analog control would probably be retained, or made available, for area regulation.

Initial installations of this type are now in operation,[20,21] and are reported to be performing satisfactorily.

Typical installations

It may be of interest at this point to look briefly at two major recent installations, which will illustrate a

number of the p[illegible] connected systems controls.

Pennsylvania–New Jersey–Maryland pool. The control area marked P in Fig. 11 is the Pennsylvania–New Jersey–Maryland pool. Companies of this group were pioneers of the "pooling" concept, in which member companies operate as a single control area with free-flowing ties and a common economic dispatch.

The 12 independently owned companies of this pool, and their intrapool and external ties to neighboring utilities, are shown in Fig. 13.

Control execution for this pool is hierarchical. At the pool headquarters in Philadelphia a net interchange tie-line bias controller acts with an analog computer unit to establish a pool lambda that will satisfy area generation requirements, and will simultaneously maintain scheduled interchanges over the 16 northern, southern, and western tie points to the utilities with which the pool interconnects.

The computer control at the central headquarters communicates this lambda value to computer-control assemblies located at the dispatch centers of the respective member companies, which in turn compute and execute corresponding economic dispatch assignments for their generating units.

American Electric Power System. The circle marked A in Fig. 11 represents the American Electric Power System. A closer look at this system and its major tie points with its principal neighbors is provided by Fig. 14.

This system, the country's largest investor-owned electric-energy producer, has pioneered in interconnected operation, as is apparent from its many ties with other utilities. Here a group of adjacent companies having common ownership operate as a single control area. Intrasystem ties are free flowing. Schedules for advantageous interchange are established and maintained for the 40 major tie points with 19 other utilities, and economic dispatch for the 38 principal generators of the system is automatically computed and maintained, all from one central location.

A new digitally directed analog system[22,23] to fulfill these functions was placed into operation late in 1964 at the company's new power control center in Canton, Ohio. Control commands are routed directly from Canton over microwave to the participating generators of the operating companies.

This installation, with its solid-state analog console, its digital computer, its individual unit approach, its use of antihunting concepts, its display arrangements for unit conditions, its arrangements for computing advantageous interchanges with its many neighbors, its tie-in with a large billing computer, and its extensive use of microwave telemetering, reflects well the present start of the art in interconnected power system controls.

I should like to acknowledge my indebtedness to a number of my associates at the Leeds & Northrup Company and to individuals of the following organizations for information helpful in the preparation of this paper: American Electric Power Service Corp., Bailey Meter Co., Control Data Corp., Ebasco Services, Inc., General Electric Co., Gilbert Associates, Hagan Controls Corp., IBM Corp., Metropolitan Edison Co., North American Power Systems Interconnection Committee, Sargent & Lundy, Southern California Edison Co., Stone & Webster Engineering Corp., Tennessee Valley Authority, and Westinghouse Electric Corp.

Figs. 1, 4, 5, and 12 are derived from reference 1; Figs. 2, 3, and 6 from reference 2; Fig. 11 is reproduced, with permission, from material of the North American Systems Interconnection Committee.

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